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Remote Sensing of Forest-Clearing Effects on Essential Fish Habitat of Pacific Salmon

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Abstract.—The rivers and streams that drain into the lower Columbia River estuary in Oregon contain essential fish habitat (EFH) for several species of Pacific salmon. Seven subwatershed basins in the Columbia River drainage basin, each containing salmon spawning and nursery habitat, were examined using remote sensing and geographic information system techniques to measure the amount and pattern of upland forest clearing. Landsat Thematic Mapper imagery from 1989 and 1992 was used to determine the cleared forest patches produced by clear-cutting. Digital Elevation Models were used to determine slope underlying cleared patches. A digital coverage (or map layer) of streams containing EFH was used to measure proximity of cleared patches to streams. The size and slope of cleared forest patches and the proximity of cleared forest patches to streams can greatly exacerbate the deposition of sediment in streams, altering stream environments and the quality of EFH. Size, slope, and proximity of cleared forest patches to streams containing EFH were calculated for the seven subwatershed basins. This analysis was performed at a landscape scale and utilized readily available broadscale data to (1) compare forest-clearing patterns across basins and (2) locate critical areas for further analysis using finer-scale data. Once critical areas had been located, a second analysis was performed using finer-scale data. The landscape-scale results indicated major differences in the spatial pattern of forest-clearing change across the lower Columbia River estuary drainage basin, with some subwatershed basins significantly altered in the three-year period. Three subwatershed basins showed a pattern of large cleared patches close to streams containing EFH. Some of these cleared forest patches were situated at least partially on steep slopes. In the three basins, Milton Creek, Young's River, and the Claskanie River run directly through large areas of cleared forest. The pattern evidenced in these critical areas is consistent with increased sedimentation and decreased stream shading characteristics, both of which can have a detrimental effect on fish habitat. Milton Creek was examined with finer-scale data, and these results showed an increased number of cleared forest patches and increased total area of cleared forest draining into streams. More cleared forest patches on steep slopes were also shown with the finer-scale data. These results provide an initial justification for performing searches for critical areas at a synoptic or landscape scale, with further research performed at a finer scale. These techniques provide a practical method to evaluate upland land-use activities and essential fish habitat.

Increasing human population and concentrated economic activities along the coasts of the United States have made coastal areas the focus of critical natural resource issues including losses of anadromous fish habitat, increases in pollution, and declines in fisheries. Although linkages between upland land-cover changes and these living resource issues have been recognized scientifically (Chamberlin et al. 1991; Beechie et al. 1994), recognition of this linkage has only recently been codified in federal law in the 1996 Magnuson-Stevens Fishery Conservation and Management Act (Magnuson-Stevens Act). Although the Magnuson-Stevens Act defined essential fish habitat (EFH) to include only "waters," the Interim Final Rule (IFR) to implement the EFH provisions (NMFS 1997) published in the Federal Register on 19 December 1997 explicitly recognizes the linkages between land-cover changes and downstream effects (62 FR 66535). The IFR advises fishery management plans to analyze the cumulative impacts of individually minor but collectively significant alterations within a watershed that impact EFH (62 FR 66553). Because of its requirements that analysis of habitat function should take place at the watershed scale, the Magnuson-Stevens Act seems to be influenced by recent research that examines habitat change at a landscape or synoptic scale. Such a synoptic approach is a precursor to addressing multiple scales of ecosystem and resource interaction, and the approach addresses two objectives. First, a synoptic approach can address cumulative impacts by simultaneously examining many watersheds in various stages of change (Chamberlin et al. 1991). Second, the quantification of regional patterns and conditions of specific environmental properties, as well as changes in specific environmental properties, allows targeting of areas of concern requiring intensive field-based research (Brickner and Ruggiero 1998).

The Columbia River estuary drainage area in northern Oregon is an excellent locale in which to examine the linkages between upland land-cover changes and effects on EFH at a landscape scale. Northwest coho salmon *Oncorhynchus kisutch* populations have been declining for the last two decades (Beechie et al. 1994), and there are definite landscape-scale changes in watersheds where streams serve as spawning and nursery habitat to coho salmon. In particular, links among forest clearing in watershed basins, increased erosion, and decline in salmon spawning and nursery habitat have been suggested (Meehan 1991; Beechie et al. 1994; Waters 1995). Forest clearing at the landscape scale in areas draining directly into lower Columbia River salmon spawning and nursery streams have been observed from remotely sensed imagery. Large patches of closed-canopy forest are cleared each year by logging practices (Cohen et al. 1998), and the size, location, and slope of cleared patches can exacerbate erosion and increase sediment in streams (Chamberlin et al. 1991). The effect of these watershed activities on EFH needs to be examined, and satellite imagery and geographic information systems (GISs) provide effective tools to measure patterns across watershed basins and to locate further study areas.

Although overall amounts of forest clearing have been measured in the Pacific Northwest (Cohen et al. 1998), our work provides a quantitative description of important spatial patterns of upland forest-clearing activities. We describe seven subwatershed basins of the lower Columbia River drainage basin that contain EFH for several salmon species. Our first objective was to characterize forest clearing in each of the seven subwatershed basins based on the following spatial variables relevant to increased erosion: size of cleared forest patch, proximity of cleared forest patch to a stream containing EFH, and slope of cleared forest patch. The analysis was performed at a landscape scale, using readily available digital data that covered the entire study area. These data were at a coarse spatial resolution and provided only medium amounts of detail. Once areas of concern were located, our second objective was to perform similar analyses with large-scale data for a small area with finer spatial resolution and more detail.[1] Large-scale data are less easily available, however. Thus a method is presented that at a landscape scale characterized differences between upland land cover changes in watershed basins and identified areas with potential erosion problems. The method highlights some of the effects on measurement associated with analyses using multiple-source scales. This analysis is based on simple, generally accepted concepts regarding the effects of forest clearing on stream water quality (i.e., clearing of large patches of forest, clearing of forest patches on steep slopes, and clearing of forest patches that drain into streams can increase the deposition of sediment into streams, which can be detrimental to EFH). In addition, this analysis is considered to be the initial step in modeling functional change to EFH based on upland alterations.

Forest Clearing and Salmon Habitat

Coho salmon utilize streams in the lower Columbia River area during several stages of their reproductive and early life history. In this area, adult coho salmon usually enter spawning streams from

[1] This paper distinguishes between cartographic scale, which refers to data, and geographic scale, which refers to geographic extent of coverage. Large-scale data refers to data with more detail and less data generalization, and small-scale data refers to data with less detail and more generalization. Landscape-scale or synoptic-scale analysis refers to analysis that covers broad areas, that is, watersheds or regions.

September to January, during periods of high runoff. For spawning adults, essential fish habitat is composed of pools and riffles with pea- to orange-size gravel in which adult females create redds and spawn (Chapman 1988). Eggs residing in the redds develop during the winter and hatch in early spring, and the embryos remain in the gravel until they emerge in May or June. The emergent fry occupy pools and shallow stream margins among submerged woody debris while they grow into juveniles during the fall and winter. The juveniles usually spend one winter in streams before migrating to the sea in spring (Meehan and Bjornn 1991). During these stages of growth, salmon EFH consists of complex stream habitat that is shaded with tree-lined banks (promoting appropriate stream temperature levels) and contains large and small woody debris. Coho stock numbers have plummeted in this century due to a number of factors including ocean conditions, overfishing, and loss of freshwater habitat essential for spawning and rearing (Baker 1995). The National Marine Fisheries Service considered listing wild Columbia River coho as "threatened" under the Endangered Species Act in 1998, and wild Columbia River coho are considered to be extinct above the Bonneville Dam.

Much research on the relationship among forest practices, sediment, and salmonid reproduction has been applied to anadromous salmon in the Pacific Northwest. We are indebted to reviews provided by Meehan (1991) and Waters (1995). The effects of forest clear-cutting on stream ecosystems are complex. Clear-cutting can produce changes in stream temperature, dissolved organic content, nutrient loads, and suspended and deposited sediment (Meehan 1991). Forest clear-cutting exacerbates surface erosion as a result of changes in the distribution of precipitation that reaches the ground, the amount of precipitation intercepted or evaporated by vegetation, and the amount of water stored in the soil (Waters 1995). Clear-cutting also eliminates root structures and exposes mineral soil to accelerated surface erosion. In addition to surface erosion from cleared slopes, there is extensive evidence that logging roads increase mass movement of soil to streams, and clearing near streams increases the likelihood of bank failures and landslides (Reid and Dunne 1984).The effects of forest clearing and altered suspended and deposited sediment loads on the composition and quality of spawning gravel, and the influence of clearing and sediment loads on the survival and condition of emerging fry, are also complex. Although many studies indicate that sediment can have both a positive and negative effect on salmonid growth and reproduction, excessive fine-grain (<2 mm) sedimentation from clear-cut areas and logging roads in the Pacific Northwest is detrimental to salmon (Reid and Dunne 1984; Chamberlin et al. 1991; Meehan 1991). As sediment yield from logged areas increases, several stream characteristics change. Stream turbidity fluctuates with deposition events (Newcombe and MacDonald 1991). As suspended sediment settles, stream gravel permeability decreases (Moring 1982; Scrivener and Brownlee 1982), and the mean particle size of material decreases as fine particles are deposited in upper layers of the streambed (Ringler and Hall 1988). The response of coho salmon to these changes varies. Coho salmon are known to avoid highly turbid or silty water and to avoid potential redd sites covered by fine particles (Waters 1995). Once eggs are laid, a layer of fine particles from upland erosion can reduce interstitial space between gravel, slow water movement through the redd, and reduce oxygen, sometimes causing suffocation (Waters 1995). Excess deposited sediment can prevent fry from emerging through overhead stratum once hatched (Hartman and Scrivener 1990). In some cases, excessive suspended sediment can impair adult salmon respiration (Waters 1995).

The size and slope of cleared forest patches and the proximity of cleared patches to streams can greatly exacerbate the deposition of sediment in streams, altering stream environments and the quality of essential fish habitat (Chamberlin et al. 1991; Meehan 1991; Desbonnet et al. 1995). Small patches of cleared forest are less likely to produce landslides and debris flows than large patches. Cleared forest patches in contact with streams weaken stream banks and can cause stream bank failure. Cleared patches on steep slopes increase surface erosion and soil movement. Slope becomes an important factor in soil erosion when slopes are steep (>25%) (Heidtke and Auer 1993), and, as is mentioned in the following sections, many of the slopes associated with the study area are steep.

Study Area

The seven subwatershed basins that comprise the study area in the lower Columbia River drainage basin are in mountainous terrain, with elevations ranging from sea level to 978 m. Each basin contains creeks, streams, or rivers that contain essential fish habitat for salmon, and all basins drain into the lower Columbia River with the exception of basin 3, which contains the Necanicum River (Figure 1).

Modeling Upland Changes at the Landscape Scale Using GIS

A geographic information system was used to manage, manipulate, and analyze a series of geospatial data layers from the lower Columbia River basin. Landscape-scale analyses of spatially distributed data benefit from the efficient storage and analytical capabilities of GIS (Stow 1994; Burrough and McDonnell 1998), and GIS techniques have been used in the Pacific Northwest for modeling salmon habitat (Lunetta et al. 1997). However, integration of multiple layers of digital data requires consideration of data accuracy (Gong 1994). The following sections describe data uncertainty related to this study and the data sources used.

Accuracy and Data Uncertainty

Uncertainty can be introduced into data at the data source (Lunetta et al. 1991). Several standard measurements have been developed to describe this error. The positional and vertical accuracy of digital spatial data are modeled by using vertical and horizontal root mean squared error (RMSE), which assumes a random normal distribution of error. Root mean squared error is usually reported with raster and vector format data, but vector data are also subject to National Map Accuracy

FIGURE 1.—The study area in the lower Columbia River estuary drainage area in Oregon. The study area includes seven subwatershed basins that have streams containing essential fish habitat.

TABLE 1.—Projection information and data uncertainty measures for spatial data layers (NAD27 = North American Datum 1927; NAD83 = North American Datum 1983).

Data [a]	Source scale or spatial resolution	Root mean squared error	Projection system [b]	Datum; units
C-CAP land-cover change	27.5-m spatial resolution	Horizontal: 0.47 pixels or 11–12 m	UTM	NAD27; meters
1:24,000-scale USGS DEM	30.0-m spatial resolution	Vertical: 15 m Horizontal: 3–5 m	UTM	NAD83; meters
1-degree USGS DEM	90.0-m spatial resolution	Vertical: 45 m Horizontal: 120–130 m	Geographic	NAD83; decimal seconds
Watersheds	1:24,000	Horizontal: 10–15 m	UTM	NAD83; meters
Rivers and streams	1:250,000	Horizontal: 120–130 m	Lambert conformal conic	NAD83; international feet
Rivers and streams	1:24,000	Horizontal: 10–15 m	UTM	NAD83; meters
Final projection format			Lambert conformal conic	NAD83; meters

[a] DEM = digital elevation model.
[b] UTM = universal transverse mercator.

Standards (NMAS), which determine the threshold of acceptable error for a map or data layer. The NMAS state that 90% of all points on a map shall be within 0.05 cm of their true location (Bolstad and Smith 1995). These standards are scale dependent, meaning that as scale increases, error decreases. Table 1 lists data source scales, projection information, and levels of uncertainty expressed as RMSE. The integration of digital spatial data layers also introduces error in the processing flow (Davis et al. 1991; Lunetta et al. 1991; Gong 1994; Congalton 1997). The geometric rectification, projection, data conversion, and co-registration processes described below can introduce additional data uncertainty that can be measured with in-the-field verification. With the exception of the land-cover data, ground verification of introduced error was not performed for this analysis. Specific data uncertainty figures are expressed in the discussion below.

Data Sources

We used four digital data sets or layers for this analysis, with varying source scales. The term "small-scale" refers to data with less detail than "large-scale" data. The digital data consist of data layers in either raster (regular grid or cell based—usually used to depict continuous variables) or vector (linear representation—usually used to represent discrete variables) format (Burrough and McDonnell 1998). All data layers are available to the public, either from the Internet or from a free CD-ROM. Our intention was to perform the analysis using readily available data so that the method could be repeated.

Land cover.—The Coastal Change Analysis Program (C-CAP), part of the National Oceanic and Atmospheric Administration's (NOAA's) Coastal Services Center in Charleston, South Carolina, monitors change in terrestrial land cover and nearshore benthic habitats within coastal environments of the United States. The C-CAP classifies types of land cover and analyzes and monitors changes in coastal submersed habitats, wetland habitats, and adjacent uplands using remote sensing techniques (satellite imagery and aerial photography). The long-term goal of the C-CAP is to correlate changes in terrestrial regions with changes in coastal aquatic habitats and relate habitat changes to population fluctuations in living marine resources.

The change analysis used in this study is part of a C-CAP project to detect land-cover change for the area surrounding the Columbia River estuary.

This project was carried out in cooperation with the Oak Ridge National Laboratory, the Columbia River Estuary Study Task Force (CREST), the National Marine Fisheries Service (NMFS) Point Adams Field Station, and Pacific Meridian Resources. Changes were detected by comparing Landsat Thematic Mapper (TM) satellite imagery (Path 47, Row 28) for 10 September 1989 and 18 September 1992. As per C-CAP protocols (Dobson et al. 1995), the 1992 imagery was georectified and then classified by a combination of supervised and unsupervised classification techniques. Pixels that exhibited change between 1989 and 1992 were identified through spectral change analysis (band differencing between the two image dates), and these change pixels were reclassified to derive the 1989 land-cover database. The processing was accompanied by an intensive field verification effort carried out in cooperation with CREST and other local cooperators.

Field verification was carried out by two- or three-person teams, each equipped with a portable color laptop computer linked to a global positioning system (GPS). The NMFS Point Adams Field Station runs software that supports the classified data as a raster background with the road network as a vector overlay while simultaneously displaying live GPS coordinates. The GPS is equipped with an external antenna that can be mounted to the top of any vehicle. Personnel can use the field station to efficiently navigate between ground points of interest. Accuracy assessment points were generated with Erdas Imagine software using a stratified random sample. To make the acquisition of field reference data more practical, a 20-pixel buffer area around roads (i.e., 10 pixels on either side of the road), including logging trails, was created. Using this technology in the CREST study area, 600 random sites were visited for the 1992 classification, and 100 random sites of potential change were visited in May 1996 (USDOC 1997). Overall accuracy for the 1992 classification was 90%, and overall accuracy for the change data were 92%. Horizontal error was less than one-half pixel for the 1989 and 1992 products, or between 12 and 15 m (for full metadata, see USDOC 1997). The complete land-cover change detection product is available at no cost from the NOAA Coastal Services Center in a format that is easily incorporated into a GIS.

Both the spatial and spectral resolution of the TM data make forest clearing discernible. Forest clearing radically alters the spectral response of the target area on the ground in both the visible and near-infrared portions of the spectrum, to which the TM sensor is sensitive. The data are in raster format with a ground resolution of 27.5 m. The accuracy figure found for the C-CAP data corresponds to the accuracy figure found in a recent study of forest clear-cuts in the Pacific Northwest that used TM data. Cohen et al. (1998) reported accuracy of TM imagery-classified clear-cuts in excess of 90% using a change-detection algorithm similar to the algorithm described in this study.

Rivers and streams.—Location of streams containing salmon spawning habitat were acquired from the NMFS in Newport, Oregon. These data contain a 1:250,000-scale stream network. The spatial data have been linked to NMFS fisheries salmon data including dam location, river reach files, and location of salmon species habitat. The data were available for all seven subwatershed basins in the study area.

A coverage of hydrography at 1:24,000 scale was obtained for the Trenholm 7.5-min quadrangle in Oregon from the Internet site provided by the Saint Charles County Geographic Information System.[2] These large-scale data depicted more streams than the 1:250,000-scale layer and included greater detail (Figure 2). Data uncertainty for each layer varies with scale. National Map Accuracy Standards are 125 m for the 1:250,000-scale data layer and 12 m for the 1:24,000-scale data layer, and the reported RMSE is 100–130 m and 7–18 m for the 1:250,000- and 1:24,000-scale data layers, respectively (Bolstad and Smith 1995).

Watershed basins.—Seven subwatershed units were used in this study. These units were compiled by the Oregon Department of Water Resources from 1:24,000-scale base maps. The seven subwatershed basins are numbered 2, 3, 4, 16, 21, 25, and 29, and they vary in size from 30,000 to over 80,000 ha (Figure 1). The data also were downloaded from the Internet site provided by the Saint Charles County Geographic Information System.[2] The reported RMSE for these data are 7–18 m (Bolstad and Smith 1995).

Digital Elevation Models.—Digital Elevation Models (DEMs) provide elevation above sea level in raster format. Two base scales for DEMs are currently available: the 7.5-min (30-m) DEM data constructed from 1:24,000-scale topographic maps, and the 1-degree or three-arc-second (90-m) model (1:250,000 scale), both provided by the U.S. Geo-

[2] For more information, see http://www.sscgis.state.or.us.

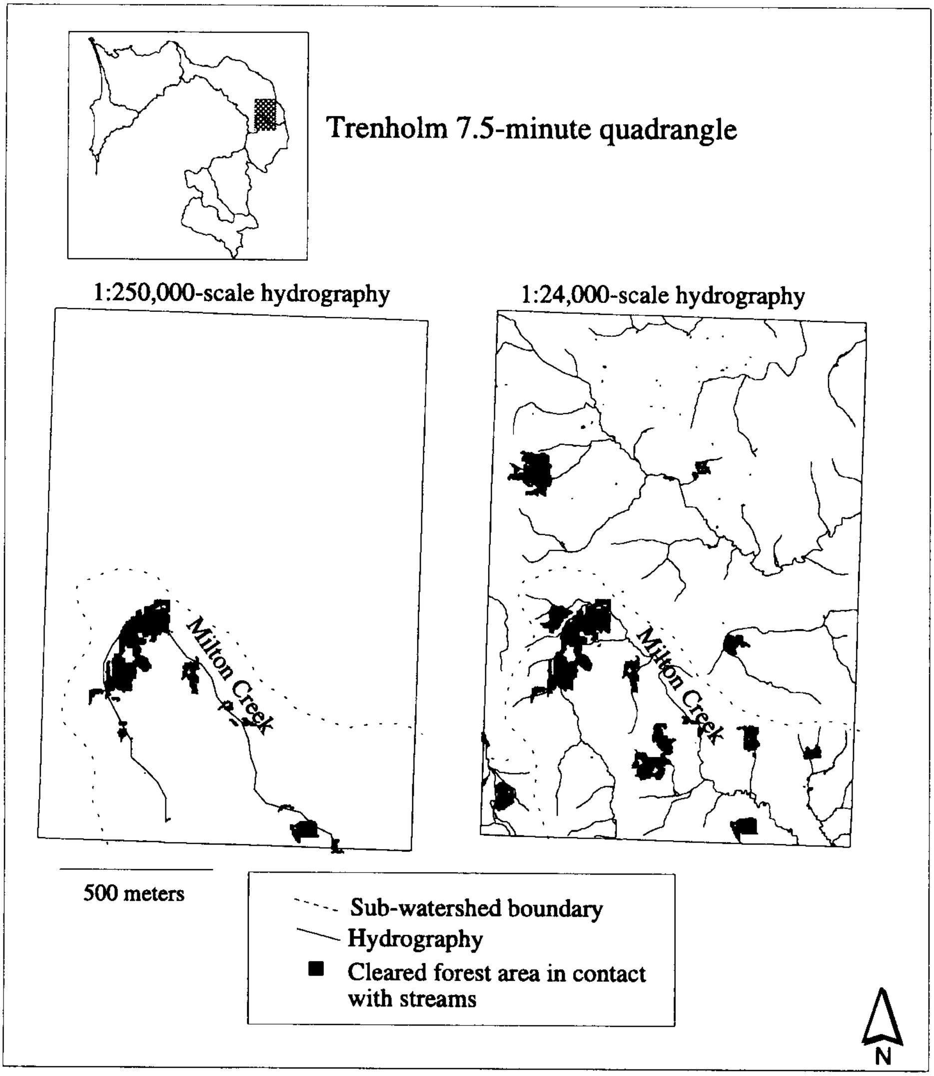

FIGURE 2.—Trenholm 7.5-min quadrangle hydrography with 1:250,000-scale data (left) and with 1:24,000-scale data (right) showing number and size of patches in contact with streams.

logical Survey. Digital Elevation Models of 1:24,000 scale were not available for the entire study area, so the initial slope measurements for the entire area were calculated from the 1-degree data. Four 1:250,000-scale DEMs were used for the landscape-scale analysis: Vancouver-east, Vancouver-west, Hoquiam-east, and Hoquiam-west. These DEMs were downloaded directly from the U.S. Geological Survey Geo-Data Internet site.[3] A 7.5-min DEM for the Trenholm 7.5-min quadrangle was downloaded from the Internet site provided by the Saint Charles County Geographic Information System.[2] Vertical RMSE for the 1:24,000-scale data are 15 m or better, and horizontal RMSE is 3–15 m. Vertical and horizontal RMSE for the 1:250,000-scale DEM is commensurate with the RMSE of the 1:250,000-scale maps, at around 125 m.[3]

The combination of data of different source scales requires consideration of data detail. Specifically, 1:24,000-scale vector data will provide more detail than 1:250,000-scale data. The larger-scale hydrography contains more detailed streams and more higher-order streams. Elevation values pro-

[3]For more information, see http://edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html.

vided by DEMs can also vary with source scale, but the relationship is usually linear (Isaacson and Ripple 1990).

Methods

Preprocessing

The vector data sets used were provided by the source agencies in either Arc/INFO coverage format or ArcView shapefile format.[4] The C-CAP data were converted from Erdas Imagine image format to Arc/INFO GRID format without change in spatial resolution or projection. Digital Elevation Model data were converted to Arc/INFO GRID format. All data were examined and analyzed in ArcView 3.0 (ESRI 1998). The seven subwatershed basins each contained streams that had salmon spawning and rearing habitat, and each basin was completely within the extent of the C-CAP coverage. By converting these seven watershed basin boundaries to each of the original projections, the study area was used as a mask to cut out the C-CAP data layer, the DEM data layer, and the stream data before reprojection.

Geographic information system analyses of multiple layers of spatial data require that the features in all layers be registered to a common projection and grid system (Lunetta et al. 1997). For this project, all vector coverages and raster grids were reprojected from native format to Lambert conformal conic format to reduce error (Table 1). Resampling of the raster coverage used the nearest-neighbor method. Error estimates derived for the Lambert projection system indicated a maximum error of 0.053% for the entire state (compared to a maximum error of 0.29% for the Universal Transverse Mercator [UTM] projection system zone 10) and a mean error of 0.017% for the entire state (compared to 0.073% for UTM zone 10) (Snyder 1987).[2] In the northern Oregon study area, error was minimized due to the placement of a second standard parallel through the area at 45°30 N; maximum error as a result of the projection system was 0.03%.

Areas of forest clearing between 1989 and 1992 were defined as areas that showed conversion from forest to grassland or conversion from forest to bare ground. The C-CAP data layer depicting cleared forest was converted from raster to vector, yielding an overlay of vector polygons, or patches. This process did not alter areal measurements. Before reprojecting the DEM, the four 1-degree elevation models were joined and clipped to the study area. The 1-degree and the 7.5-min DEMs were reprojected using a nearest-neighbor resampling algorithm. A slope coverage derived from the 1-degree DEM and the 7.5-min DEM using standard GIS techniques yielded percent slope for each pixel (Burrough and McDonnell 1998).

Spatial Data Analysis

The size and slope of cleared forest patches and proximity of cleared patches to streams can greatly exacerbate the deposition of sediment in streams (Chamberlin et al. 1991; Meehan 1991; Desbonnet et al. 1995). Size, slope, and proximity were measured in the GIS as described below. Using the vector layer of cleared forest patches with the layer of subwatershed basins, the following spatial characteristics of cleared forest patch size were measured for each basin: total amount of forest cleared, number of cleared patches, mean size of cleared patches, and largest cleared patch.

The proximity of cleared areas to the streams closest to them was calculated for each basin. First, a centroid for each cleared forest patch was determined, and the distance from the centroid of each cleared forest patch to the closest stream containing essential fish habitat was calculated as a Euclidean distance. The results of the distance calculation were added to the cleared forest patch coverage as an additional attribute, and mean distance from stream for all cleared forest patches was calculated for each basin. Second, cleared forest patches that were immediately in contact with a stream containing EFH were determined by using a spatial query that determined the spatial intersection between the stream coverage and the individual cleared patches. This new layer was used to calculate the number of cleared forest patches in contact with streams, mean sizes of cleared forest patches in contact with streams, and largest cleared forest patches in contact with streams. The DEM data were used to calculate percent slope across the study area to analyze the relationship between forest clearing and slope. The slope layer was resampled (i.e., converted from one spatial resolution to another) to the spatial resolution of the cleared forest layer. Cleared forest patches that were in contact with streams containing EFH were queried for their maximum slope

[4] Reference to trade names does not imply endorsement by the National Oceanic and Atmospheric Administration.

TABLE 2.—Spatial characteristics of cleared forest patches in subwatershed basins in the lower Columbia River basin calculated by evaluating changes in satellite imagery from 1989 and 1992 using a geographic information system.

Basin	Total forest cleared in basin (ha)	Percent of forest cleared in basin	Number of cleared patches	Mean size of cleared patches (ha)	Maximum size of cleared patches (ha)
2	2,709.0	6.8	1,836	1.3	196.4
3	92.2	0.4	350	0.2	9.8
4	1,945.3	7.9	4,140	0.4	75.0
16	1,529.8	13.8	1,744	0.8	152.5
21	1,069.8	9.4	1,686	0.5	64.7
25	538.8	4.6	457	0.9	76.9
29	609.0	3.5	894	0.6	41.1

value, and the maximum slope values for each cleared forest patch were classified as critical (>25%) or noncritical (<25%). The threshold for determination of critical slope is based on Heidtke and Auer (1993). The additional item of maximum slope underlying each cleared forest patch was added to each cleared forest patch centroid point as an attribute. Mean size and largest size were calculated for cleared forest patches in contact with streams having slopes in excess of 25% grade.

From these results, four critical sites were identified that met the following criteria: largest cleared forest patches in contact with streams, and the largest cleared patches near water on steep slopes (>25% grade). We attempted to examine each of the four target areas with large-scale data, but large-scale stream data and DEM data were available for only one of the four sites. This fourth site along Milton Creek is contained in the Trenholm 7.5-min quadrangle. Number of cleared patches, mean size, maximum size, and total area of cleared forest patches in contact with streams were calculated for both 1:250,000-scale and 1:24,000-scale stream data. Number of cleared patches, mean size, maximum size, and total area of cleared forest patches in contact with streams on a steep grade (>25% grade) were calculated using both the 7.5-min and the 1-degree DEMs.

Results

Forest clearing varied widely by basin, and in the three years covered by the remotely sensed data, a measurable amount of forest cover was removed from several of the watersheds (Table 2). The entire study area experienced a 2% removal rate annually, three times larger than the amount reported by Cohen et al. (1998). Basins were classified into three groups: heavy forest harvesting (basins 2, 4, 16, and 21); slight harvesting (basin 3); and intermediate forest harvesting (basins 25 and 29). In subwatershed basins 4 and 16, over 1,500 ha of forest cover were cleared in 3 years, and over 2,500 ha were cleared in subwatershed basin 2. Figure 3 shows the pattern of forest clearing throughout the study area. The number of cleared patches was as many as 4,140 in basin 4, and the number of cleared patches demonstrated that basins 2, 4, 16, and 21 were more heavily harvested than the other basins. Mean size of cleared patches varied from 0.2 ha (basin 3) to 1.3 ha (basin 2). Large clear-cuts greater than 100 ha were found in basins 2 and 16, and in basins 4, 21, and 25, clear-cuts greater than 60 ha were found. Subwatershed basin 3, a heavily forested area, remained relatively unchanged during the three-year time period.

The relationship between cleared area and proximity to stream varied by drainage basin. Table 3 lists the change in each basin with respect to cleared forest patch proximity to streams. Forest clearing occurred closer to streams in basins 2, 16, and 25 than in the other basins. More patches were in contact with streams in basins 2 and 16 than in other basins. In basin 16, a total of 231 ha of forest, or nearly 15% of total clearing in basin 16, was cleared in areas that were in contact with streams. In basin 16, more than half of the cleared area in contact with streams was found in one large contiguous patch of cleared forest over 150 ha in size. Basin 2 also had a large contiguous cleared forest patch that drained into a stream containing EFH. In basin 2, the mean size of cleared patches in contact with streams was large (19.3 ha) and indicated the presence of larger-than-average clear-cuts draining into streams. In basin 3, the mean size of cleared forest patches was less than 1 ha, and these patches were further away from streams.

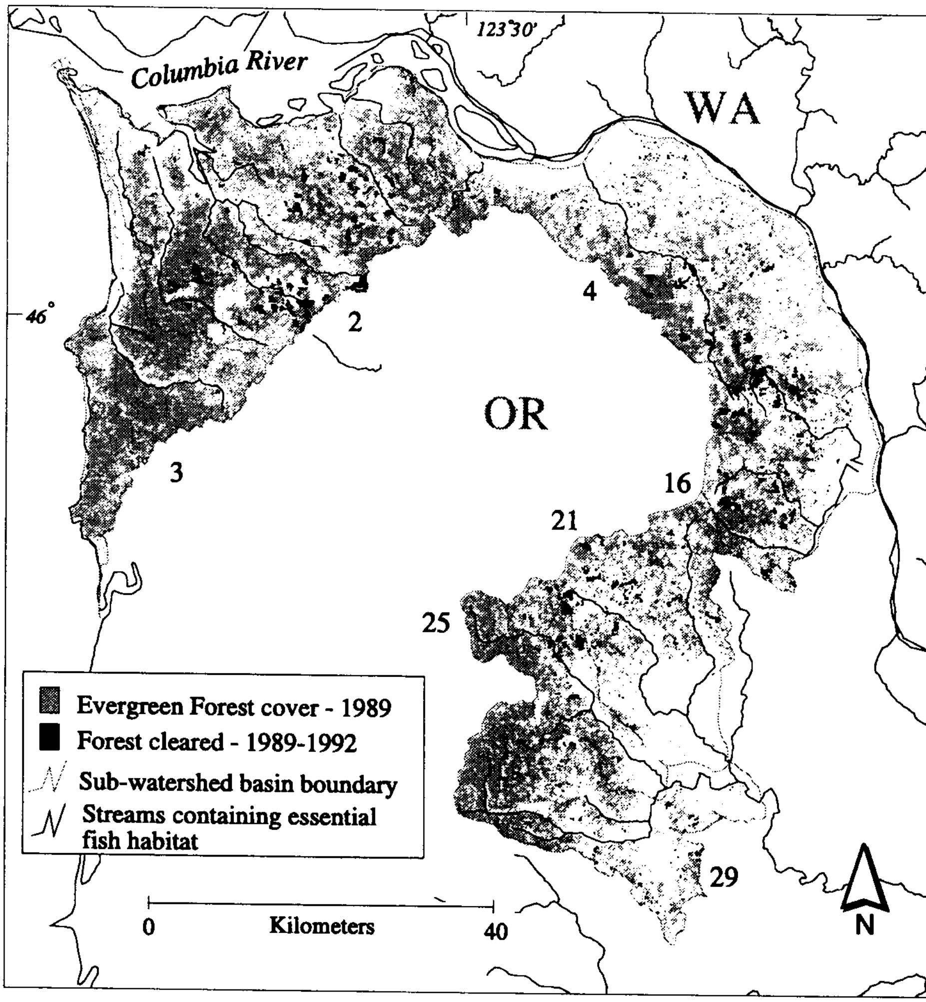

FIGURE 3.—Forest cover and forest clearing in seven subwatershed basins in the lower Columbia River basin, Oregon, between 1989 and 1992. Cleared forest is estimated from Coastal Change Assessment Program (C-CAP) data. Subwatershed basins are numbered.

Consideration of the slope of harvested patches in contact with streams containing EFH is crucial to evaluating potential disturbance. Several of the cleared forest patches in contact with streams were on partially steep slopes. Table 4 lists the size characteristics of cleared patches that contacted streams on steep slopes (>25% grade). Although the amount of forest clearing that contacted streams on steep slopes was less than the overall amount of clearing in contact with streams, three basins mentioned above (2, 4, and 16) deserve mention here. Over 8 ha of cleared forest patches in basins 2 and 16 were in contact with streams containing EFH, and at least some portion of these cleared patches were on steep slopes. The patches listed in Table 4 are small cleared forest patches (0.13–1.32 ha) found in river valleys with steep walls, but the patches may contribute significantly to downstream effects on habitat because of their steep slopes. Basins 2 and 4 had single cleared patches greater than 1 ha located on partially steep slopes that were in contact with streams.

Four critical areas in basins 2, 4, and 16 contained the largest cleared forest patches in contact with streams and the largest cleared forest patches in contact with streams on partially steep slopes. The locations of all four critical areas in the study area are displayed in Figure 4, and Figure 5 provides a close-up view of the critical areas. Area "a" in Figure 5 shows forest clearing in basin 2 along the Young's and Klaskanine rivers and the south fork of

TABLE 3.—Proximity of cleared patches to streams containing essential fish habitat in seven subwatershed basins of the lower Columbia River basin, 1989–1992.

Basin	Size of cleared area immediately in contact with a stream (ha)	Mean distance from cleared patches to streams (all patches) (m)	Number of cleared patches immediately in contact with a stream	Mean size of cleared patches immediately in contact with a stream (ha)	Largest cleared patch immediately in contact with a stream (ha)
2	173.12	1,609.4	129	19.3	103.3
3	1.72	4,136.3	15	0.8	9.8
4	40.54	2,942.7	70	0.7	15.3
16	231.32	1,392.0	128	2.0	152.5
21	3.18	2,344.2	30	0.2	2.3
25	36.49	1,613.2	24	1.6	23.1
29	14.86	2,938.1	11	1.6	8.6

the Klaskanine Rivers; the largest area of clearing (103 ha) is along Young's River. Area "b" in basin 2 (Figure 5) shows a closer view than in area "a" of the 28.3 ha of clearing along Klaskanine River. Area "c" shows clearing along the Claskanie River in basin 4; this clearing is found on partially steep slopes. Area "d" in basin 16 shows Milton Creek, which includes the largest clear-cut found in the study area (152.5 ha). Area "d" was covered by the Trenholm 7.5-min quadrangle, and finer-scale data were only available for this area (see Figure 2).

Analysis of the Trenholm 7.5-min quadrangle that covers area "d" reveals the changes in measurements that can result from changes in data scale. The 1:24,000-scale stream data and information resulting from the 7.5-min DEM are presented in Table 5 and compared to 1:250,000-scale data and information resulting from the 1-degree DEM. The 1:250,000-scale and 1:24,000-scale hydrography are mapped for the area covered by the Trenholm 7.5-min quadrangle (total area 13,458 ha) in Figure 2. Areas of cleared forest in contact with streams are shown for each scale. The 1:24,000-scale hydrography contains more detailed streams and more higher-order streams. Because of this mapped detail, the 1:24,000-scale hydrography recorded more cleared forest patches intersecting with the streams (69 patches compared to 15) and more total cleared area draining into the streams (461 ha compared to 208 ha) than the 1:250,000-scale hydrography. The mean size of cleared forest patches decreased with the 1:24,000-scale data as smaller patches of cleared forest were found that intersected with streams, although the large (152 ha) patch remained the maximum-sized patch according to both sets of stream data. Despite the lower accuracy of the 1:250,000-scale data, the landscape-scale analysis successfully located the largest cleared forest patch. The slope information yielded similar results. Although none of the cleared forest patches located using the 1:250,000-scale stream data were on partially steep slopes as depicted by the 1-degree DEM, when the analysis was performed using 1:24,000-scale stream data and the 7.5-min DEM, several cleared patches in contact with streams were identified on partially steep slopes. A total of 331.6 ha of cleared forest land intersecting with the streams in the 7.5-min quadrangle occurred on partially steep slopes. When the 7.5-min DEM was used for slope analysis, the largest cleared patch in the study area (shown in diagram "d" in Figure 5 and in both diagrams in Figure 2) was shown to contain partially steep slopes. This change in slope value was caused by the greater heterogeneity of the 7.5-min DEM data. With 7.5-min DEM data, elevation is captured with more detail, and in areas of steep terrain this can result in greater variance in slope value (Isaacson and Ripple 1990).

Discussion

A synoptic or landscape-scale analysis of forest clearing across seven subwatershed basins revealed differing patterns of forest clearing by basin and successfully targeted areas for larger-scale examination of the effects of forest clearing on essential fish habitat. Areas that showed the most cleared forest exhibited a pattern of clearing that could be detrimental to EFH. The forest clearing pattern shown in subwatershed basins 2, 4, and 16 has the potential to increase soil erosion from upland clearing adjacent to streams, to increase instream soil deposition from bank failures, and to change shading alongside streams. These habitat alterations can be detrimental to the reproduction and survival of salmonids. In basins 2, 4, and 16, in which 7, 8, and 14%, respectively, of forest cover was cleared dur-

TABLE 4.—Size characteristics of cleared patches in contact with streams containing essential fish habitat on steep slopes (>25% grade).

Basin	Total area in contact with streams (ha)	Mean size of cleared forest patch (ha)	Size of largest cleared forest patch (ha)
2	8.10	0.12	1.26
3	1.50	0.14	0.33
4	5.00	0.11	1.32
16	8.60	0.13	0.66
21	3.40	0.15	0.39
25	0.90	0.13	0.13
29	0.90	0.13	0.26

ing the 3 years covered by the study, larger areas were cut and clearing occurred closer to streams and partially on steeper slopes than in the other basins studied. Three streams in particular, Milton Creek (basin 16), Young's River (basin 2), and Claskanie River (basin 4) had large cleared patches along streams, and some of these patches were on partially steep slopes. These areas should be targeted for future research (see below). In basin 16, nearly 20% of logging patches were in contact with streams, and one cleared patch along Milton Creek was over 150 ha in size. This area in the Trenholm 7.5-min quadrangle along Milton Creek was examined with large-scale data, and the results of those examinations strengthened results obtained from the landscape scale. The larger amount of detail in the 1:24,000-scale stream data and the 7.5-min DEM data reveal more cleared forest patches in contact with streams, more cleared forest patches on partially steep slopes, and a larger total area affected. These results provide an initial justification for searching for problem areas at a synoptic or landscape scale, with further research performed at a finer scale. Further fine-scale research includes modeling soil erosion from cleared areas and linking results with salmon count data. In addition, these results reveal the effect on measurement that often results from the use of multiple-scale data (Cao and Lam 1997).

Quantification of forest-clearing patterns is an important predecessor to determining possible links between land-cover change and downstream effects on structure and function of essential fish habitat and ultimately on salmonid production. This project provides a method for use in salmon restoration research that expands upon habitat modeling by introducing accurate land-cover change data. The project also serves as a precursor to functional analysis and soil-erosion and nonpoint source modeling at the watershed scale. Further, these techniques provide an inexpensive and thorough method to evaluate upland land-use activities and essential fish habitat.

Lessons Learned

Geographic information systems allow the integration of diverse data for overlay analysis, change assessment, and habitat suitability modeling. Landscape-scale analysis of uplands allows comparisons

TABLE 5.—Comparison of proximity measurements and slope measurements between 1:24,000-scale and 1:250,000-scale stream data and the 1:24,000 and 1-degree Digital Elevation Model for the Trenholm 7.5-minute quadrangle.

Data source	Number of cleared forest patches	Number of cleared patches on steep grade (<25%)	Mean size of cleared forest patches (ha)	Maximum size of cleared patch (ha)	Total cleared area draining into streams (ha)
			Rivers and Stream data		
1:24,000-scale	69		6.6	152.5	461.1
1:250,000-scale	15		13.8	152.5	208.3
			Digital Elevation Models		
7.5-minute DEM (1:24,000 scale)		9	36.8	152.5	331.6
1-degree DEM		0			

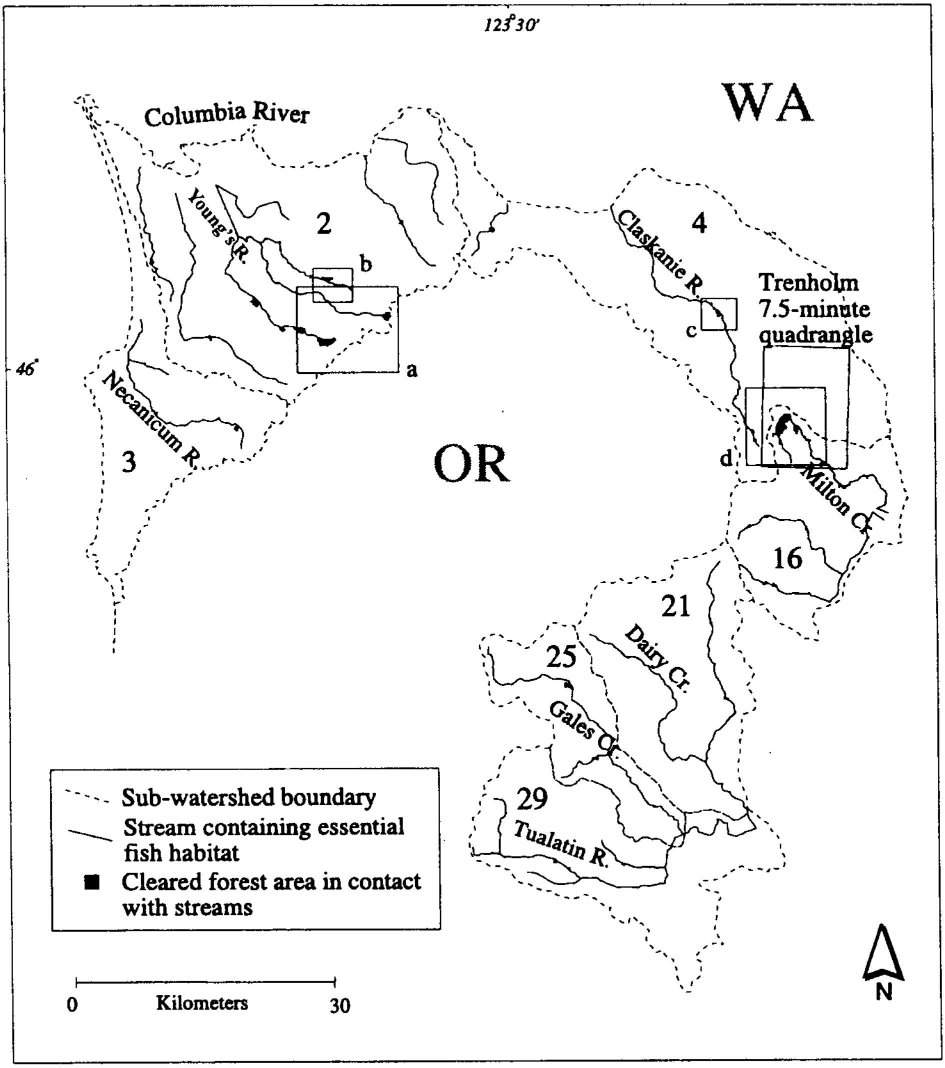

FIGURE 4.—Distribution of patches of cleared forest in seven subwatershed basins in the lower Columbia River basin, Oregon. The locations of four areas depicted in Figure 5 are also shown.

across basins while simultaneously examining many watersheds in various stages of change and allows targeting of areas of concern that require intensive field-based research (Brickner and Ruggiero 1998). This method of landscape-scale analysis should be applied elsewhere.

Continued research is needed to address the problems of integrating geographic data from multiple sources and scales. Although landscape-scale analysis successfully located critical areas with large patches of cleared forest in contact with streams and some patches on partially steep slopes, the accuracy of the small-scale data requires that research with large-scale data should follow to substantiate results. This procedure was performed for one area in this study because large-scale data were not available for the entire area. Wherever possible in similar studies, multiscale analysis should be performed to confirm landscape-scale results. In addition, the results of large-scale analysis should be verified with field sampling. Data uncertainty introduced in the processing flow, in particular co-registration uncertainty, should be examined in the field before any intensive field-based research. Future analysis will build on this technique to model functional change as a result of changes in land-cover patterns. The method described here forms an important adjunct to salmon habitat studies and links the management of whole

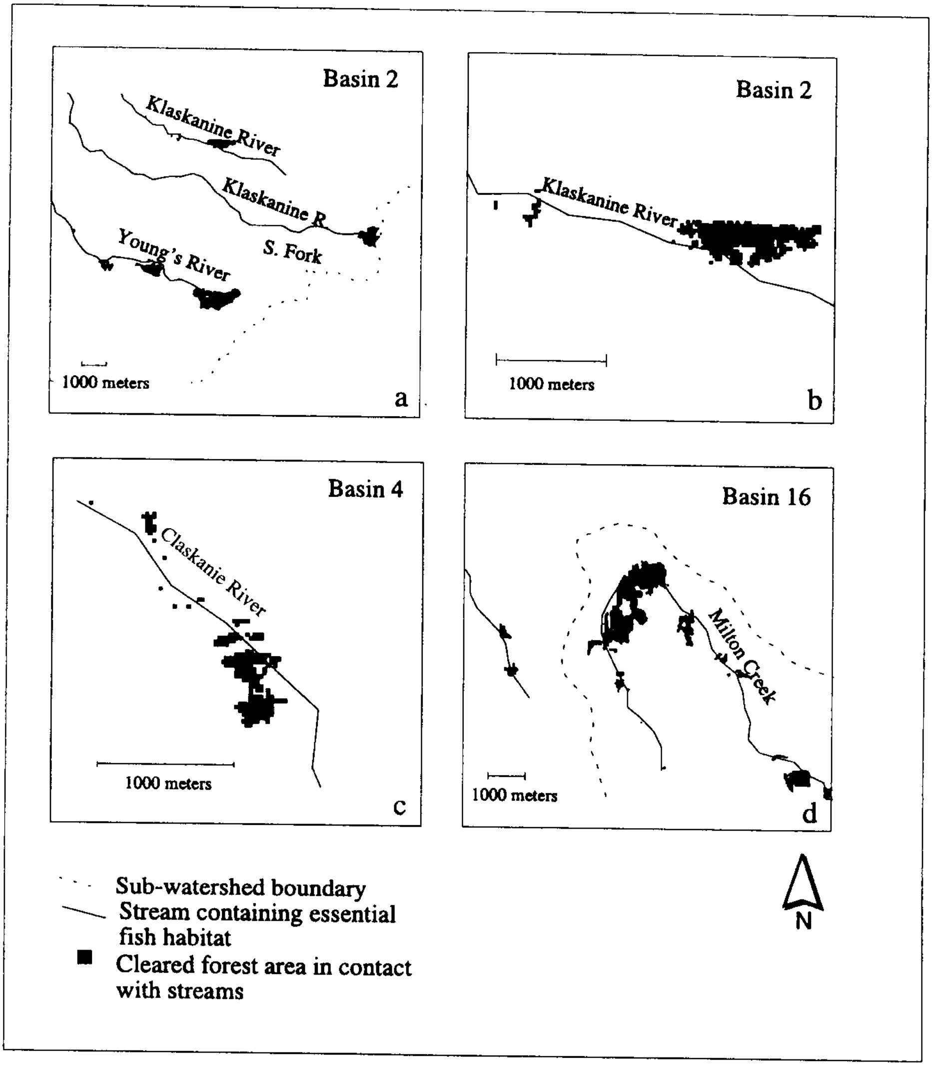

FIGURE 5.—Four specific problem areas identified from seven subwatershed basins in the lower Columbia River basin, Oregon: (a) in subwatershed basin 2, showing areas draining into streams containing essential fish habitat (EFH); (b) in subwatershed basin 2, showing areas that drain steep slopes and flow into streams containing EFH; (c) in subwatershed basin 4, showing areas that drain steep slopes and flow into streams containing EFH; and (d) subwatershed basin 16, showing areas draining into streams containing EFH.

watershed ecosystems with management of anadromous fish. Finally, these techniques should be used to evaluate salmonid essential fish habitat from Washington to California.

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